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The Space Applications Industrial Laser System

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Abstract

A joint program (Center for Space Transportation and Applied Research, University of Tennessee Space Institute, University of Waterloo, and Lumonics Corporation) is underway to develop a YAG laser based materials processing workstation to fly in the cargo bay of the Space Shuttle. The system will be capable of cutting and welding steel, aluminum and Inconel alloys of the type planned for use on the space station Freedom. As well as demonstrating the ability of a YAG laser to perform remote (fiber-optic delivered) repair and fabrication operations in space, fundamental data will be collected on these interactions for comparison with terrestrial data and models.

The flight system, scheduled to fly in 1995, will be constructed as two modules to fit into standard Get Away Special (GAS) canisters. The first can holds the laser and its power supply, to be constructed by the industrial partner, Lumonics Industrial Processing Division. The second canister has the materials processing workstation and the command and data acquisition subsystems. These components will be provided by the groups at UTSI and the University of Waterloo. The cans are linked by a fiber-optic cable which transmits the flight from the laser head to the workstation.

This paper delineates the activities, requirements and accomplishments for the SAILS project to date.

Introduction

The UT-Calspan Center for Space Transportation and Applied Research (CSTAR) is one of 17 NASA Centers for the Commercialization of Space (CCDS). The mission of CSTAR is to team with industry and academia in the development of new and innovative space technologies. The SAILS program has been developed under this mission because of its broad potential to benefit industry, academia, and government through advanced laser materials processing technology.

The long term space missions planned by NASA will require some form of machining and repair capability. The proof-of-concept flight in 1995 will firmly establish the YAG laser as a viable materials processing tool for space applications. Follow-on phases to the program will develop the infrastructure necessary for implementation on long term space structures by the end of the century.

As the lifetime and complexity of space structures increase, the ability to construct, maintain and repair these structures in space must also be improved. The industrial laser represents a possible solution to the problem of conducting multiple task manufacturing and repair operations at remote, hostile locations such as an orbiting platform.

The purpose of the Space Applications Industrial Laser System (SAILS) project is to demonstrate the capability to employ a YAG laser processing facility in space and to perform practical laser materials processing operations under microgravity conditions. The objectives of this project may be grouped under the following categories:

Science: Determine the effects of gravity on welding, drilling, cutting, brazing, and soldering. Compare experimental results with models to improve predictions of process behavior in Earth's gravity and microgravity.

Space Engineering: Demonstrate viability of laser technology to perform repair and fabrication type operations in space. Applications include a laser repair kit for Space Station, manned Mars missions, and a Moon base, and a laser-based factory in space.

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Laser Engineering: Design refinement and demonstration of the industrial YAG laser to show that it has become a simple, compact, efficient and rugged tool capable of operating in any environment; in particular show the advantages of fibre optic beam delivery, including ruggedness and the ability to operate in remote and harsh environments. The Lumonic's Luxstar Laser has been chosen as the prototype from which the flight laser will be developed.

Program Status

The SAILS program, initiated in 1990, continues to progress toward a 1995 Space Shuttle flight. During FY92, NASA assigned SAILS to STS-72 with a tentative launch date of June 6, 1995. The following gives the status of several other program challenges.

Payload Flight Plan

The payload flight plan which describes in detail how the flight will be accomplished for the SAILS program was originally submitted to NASA in 1991 and received approval from the NASA Level I Payload Review Board (PRB) in March 1992. This review was primarily to evaluate the commercial merit of the program. Following Level I approval, SAILS was submitted to the NASA Level II PRB for technical evaluation. This board awarded conditional approval to the program in August 1992 subject to evaluation by each of the appropriate NASA Centers.

NASA Payload Integration

The lead for integration of the SAILS hardware has been assigned to the NASA Small Payloads Flight Division at Goddard Space Flight Center (GSFC). After a preliminary meeting between CSTAR and GSFC in September 1992, SAILS was designated as a Complex Autonomous Payload (CAP) due to its unique fiber optic interconnection requirement. The CAP also allows for an additional 1/2 canister (15") addition to the standard GAS can which may be beneficial in integrating the Lumonics LUXSTAR laser.

GSFC also has the responsibility to furnish the canisters and support services to be used for the experiment and to deliver the system to JSC for safety inspection prior to flight. One document GSFC submits to JSC is the Payload Accommodations Requirements (PAR) which defines all necessary experiment requirements and identifies all potential hazards. GSFC will work with CSTAR in development and submittal of this document to JSC for flight manifesting. A draft PAR was completed in FY92 with the final document scheduled for submittal to JSC in early 1993.

Program Schedule

As previously described, the SAILS experiment consists of two GAS canisters linked by a fiber optic delivery system. Development and fabrication of this experiment requires several integrated tasks to be accomplished by each of the three program participants. Figure 1 shows each of the major tasks required for the program.

Tasks Accomplished

Two technical milestones were reached this year in the development of the SAILS program. The ground based laboratory was completed and is now fully operational. The materials and processes to be tested in the SAILS experiment were also identified. This section will describe the features of the CSTAR laser lab and the rationale for selecting the materials to be used in the SAILS flight experiment.

CSTAR Laser Processing Lab

The Laser Materials Processing Lab at CSTAR is based on a JK701 Nd:YAG laser, operating at 1.06 μ wavelength, which was supplied by the SAILS industrial sponsor, Lumonics Industrial Products Division. This is a versatile industrial laser, capable of 400 W average power, 5 kW peak power, and pulse lengths from 0.5 to 20 ms. The laser beam is delivered to the processing enclosure by a 5 m long optical fiber. The lab has obtained two delivery fibers, of 1000 and 600 μm diameter, for high power and precision processing respectively.

The laser beam delivery fiber enters the enclosure and terminates at the laser machining head, where the beam is expanded, collimated, redirected downward and focussed onto the workpiece. The machining head is mounted on a coarse vertical slide and also contains a micrometer fine focus adjustment. The turning mirror is dichroic, reflecting the laser light and transmitting visible, to allow a video camera mounted at the top of the head to see the workpiece and permits the operator to precisely locate the area to be processed. The enclosure has been fitted with an X-Y linear translation system, capable of moving a 12x12 inch sample over a 12x12 inch area. A rotary stage can be mounted on the X-Y base, with the axis either horizontal or vertical, to enable processing cylindrical parts. The stages are driven by stepper motors and 10 microstep/full step driver

modules, giving a maximum linear resolution of 1 μm.

The sample translation system is driven by an intelligent motion control board (Oregon Microsystems PC38-4), located in an IBM AT computer. The board is capable of controlling 4 axis of linear or linearly interpolated motion or circular interpolated motion on any pair of axis. This board, with its own MC68000 microprocessor, treats the host computer as an ASCII terminal. Command sequences sent from the host, either as directly typed commands or downloaded files, are queued and executed by the motion controller, thereby freeing the host computer to perform other tasks. The motion controller is also responsible for monitoring travel limit and panic kill switches, executing an orderly shutdown in the event that one of these safety interlocks is tripped.

Digital output lines of the motion controller are used to toggle several laser functions, such as laser on, shutter open/close, and single shot output, once the laser has been placed under remote control by the operator. A serial interface between the host computer and the laser is also used to download pre-programmed pulse characteristics, and to enquire laser status information.

SAILS Material and Process Selection

As the SAILS experiment is designed to demonstrate the viability and practicality of laser materials processing in space, the processes to be tested and the materials chosen all have application in space systems. Initial trials were conducted to show that the materials could be processed with the laser power anticipated for the flight system. The materials and processes selected are shown in Table 1.

The processes all have obvious practical applications, in space or on earth. Structural joining operations (welding and brazing) will be needed in the assembly and repair of man-rated habitats. Cutting will be required for removing damaged components for repair and in the recycling of space debris. Soldering of electrical and electronic components could be accomplished remotely using a dexterous manipulator and a fiber delivered laser beam, with much less heat input to nearby components than with a conventional solder iron.

Table 2 identifies each material and a specific space application. The scientific purpose of performing each process is also described. The non-penetrated welds are most useful for comparing with similarly prepared terrestrial samples and computational models of the welding process, such as the WELDER code [1,2]. Full penetration welding samples, drills, cuts, brazes and solders produce engineering test pieces for later structural analysis. Comparison of these samples with those performed on earth will highlight the differences of performing these processes on orbit. The kapton diagnostic drills are used to record the beam size and focus height. The lead/tin weld sample simulates the condition of a deep penetration keyhole, and will be useful in predicting the performance of higher power lasers. Note that 15 material/process combinations are listed for the 16 sample positions. Two diagnostic runs on Kapton are scheduled to confirm proper operation of the system.

Tasks Underway

The tasks completed have laid the groundwork for developing programs to scientifically define and characterize the processes to be performed on orbit, and design and specify the components of the hardware to be used in flight.

Ground Studies

Preliminary studies were designed to show that the materials and processes under consideration could be processed with a relatively low power laser (see Table 3). A firm idea of the processing conditions for each sample is needed before detailed design of the flight hardware can begin. Therefore, a study to determine the precise processing parameters to be used for each sample, and to characterize the results of each process, is now well underway. As well as finding workable combinations of processing parameters, this study will eventually try to determine scaling relationships (depth and width of weld vs power, metal structure) between the flight power level and presently available ground-based laser power levels. This will permit prediction of the performance of higher power lasers operating under space conditions.

Table 4 shows the results to date of the study to determine the optimum processing parameters for each process. All parameters fall within the limitations of the flight laser system.

All materials and processes have been tested, but the parameters for those processes not completed on the chart have not been finalized.

Figure 2 shows photographs of spot and seam welds in 316L stainless steel under the conditions described in Table 4. Figures 2a and 2b show top and cross section views of spot welds performed in the 3.2 mm thick material. Figures 2c and 2d show top and bottom views of a full penetration seam weld performed in the 0.73 mm thick material. While the non-penetrated welds do show some porosity, all welds are strong and crack-free.

Figure 3 shows overview and detailed photos of a full penetration seam weld in 2219 aluminum, using 0.25 7mm of 4047 aluminum filler metal, under the conditions described in Table 4. The weld is smooth, uniform, and crack-free.

Initial process characterization and process parameter selection is nearing completion. Detailed analysis and testing of joints and the scaling study will begin in the next year.

Flight Hardware Design

The detailed definition of the laser characteristics and the results from the initial process characterization tests allowed a more detailed design of the flight hardware. Figures 4 and 5 show the current state of design for the laser and processing cans, respectively.

The laser can design is still in an early stage, as exact dimensions of the laser modules are not yet available. Initial estimates of size and weight indicate that a GAS can could be a very tight fit for a LUXSTAR laser without substantially redesigning the laser. As an alternative, other carrier geometries are being investigated. It remains to be determined whether repackaging the laser into a cylinder, or designing a rectangular GAS can type housing will be more feasible.

The materials processing can design is much further advanced. The sample matrix has been changed from a square array to a single circular pattern. The internal laser beam delivery has also been changed from a fiber to a free-space beam with moving optics. This configuration mimics current industrial laser practice of using a moving optics end effector to achieve more motion flexibility. Decoupling the motion axis also produces a more stable structure. Candidate hardware systems for many of the components in this can have been identified and many of the subsystems shown are drawn to scale. The design to this point is within the volume and weight restrictions of a GAS canister.

Objectives for 1993

As shown on the SAILS Program Schedule (Figure 1), the objectives for 1993 will consist mainly of flight hardware design and development activities. Specifically, the following technical tasks will be accomplished:

- Completion of flight hardware design for both the laser and materials processing canisters and interconnecting fiberoptic system.
- Procurement and development of the computer and control system.
- Procurement and development of the visual data system.
- Procurement and fabrication of the sample carrier.
- Fabrication of the materials processing canister.
- Begin integration and testing of flight hardware.

Conclusion and Acknowledgements

A program is well underway to develop the first laser materials processing workstation for use in space. As well as providing fundamental information on several laser-material interactions, this program will demonstrate the ability of laser processing to perform useful repair and fabrication operations in space.

This work is supported by CSTAR, under NASA grant NAGW-1195; The University of Tennessee Space Institute Center for Laser Applications, and Lumonics Industrial Products Division. Weld filler metals and brazes were provided by Lucas-Milhaupt Inc. The authors gratefully acknowledge their colleagues supporting this effort: Harald Bransch of Lumonics, Walt Duley and Grant Kinsman of the University of Waterloo and Carole Thomas of CSTAR.

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Figure 1 Task Schedule

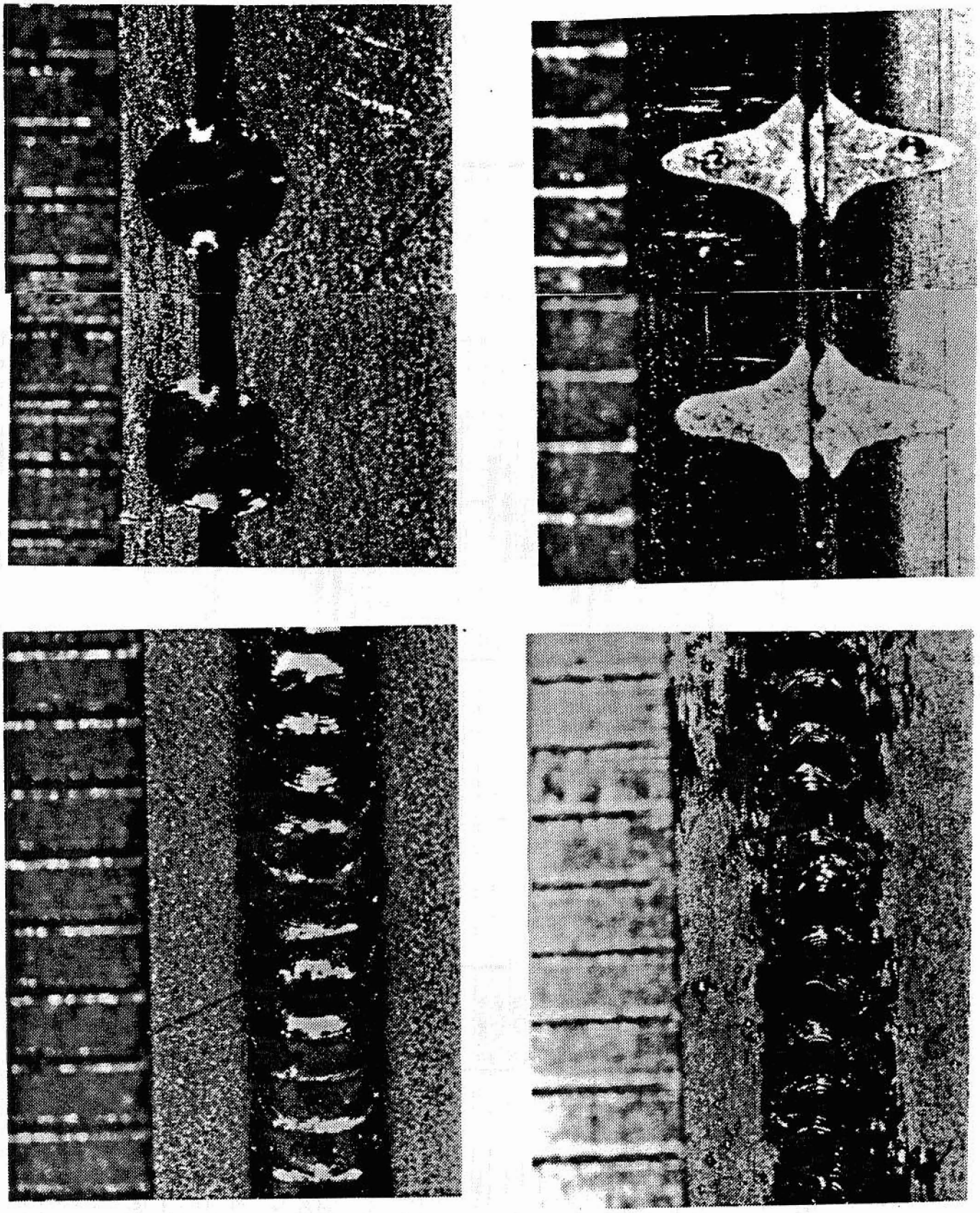

Figure 2 Laser welds of 316L stainless steel. See Table 4 for conditions. a), b) Top and side views of spot welds in 3.2 mm thick material. c), d) Top and bottom views of a full penetration seam weld in 0.73 mm thick material. Scale: 0.5 mm/div.

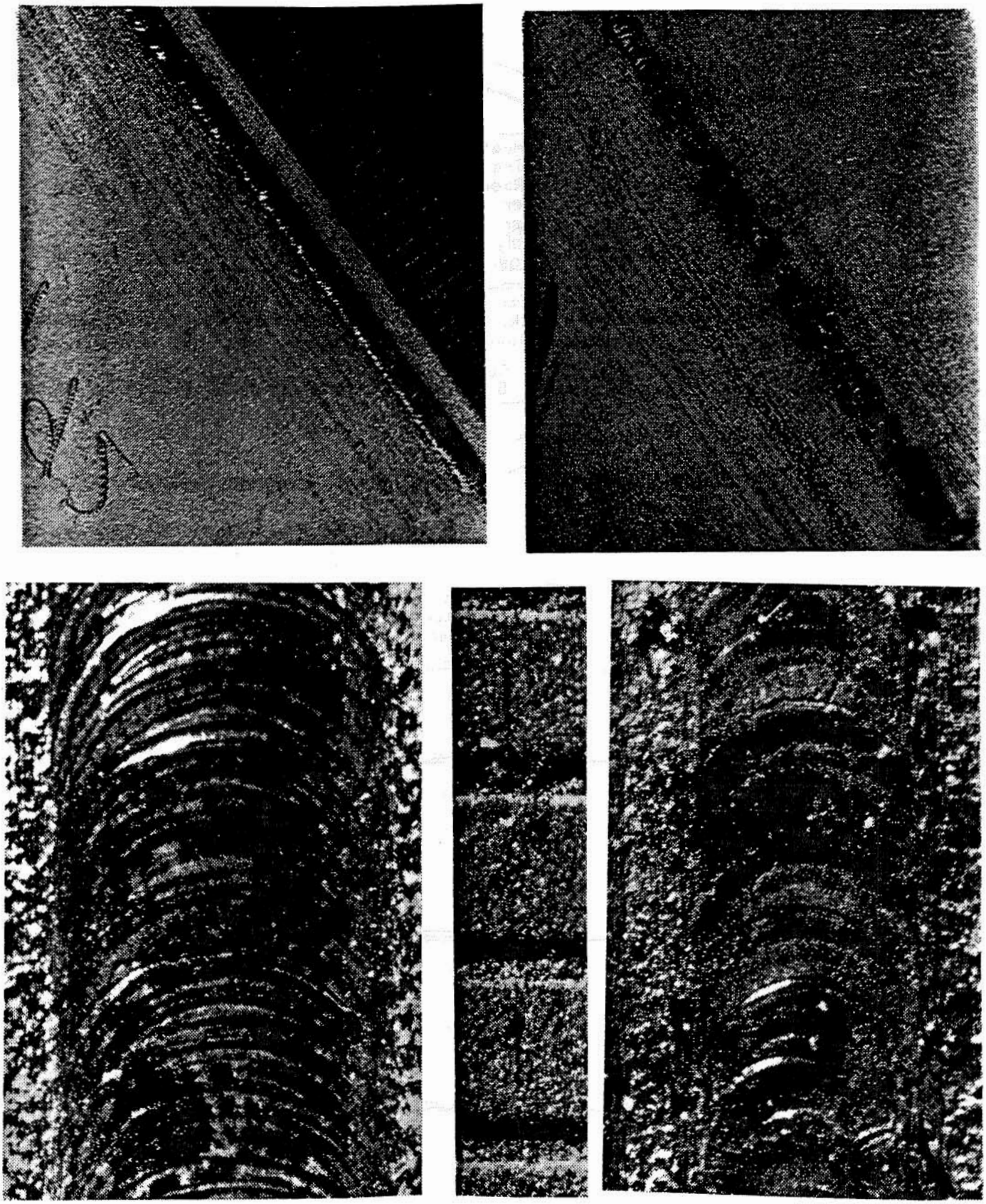

Figure 3 A full penetration laser seam weld in 2219 aluminum using 4047 aluminum filler. See Table 4 for conditions. a), b) overview. c), d) closeup. Scale: 0.5 mm/div.

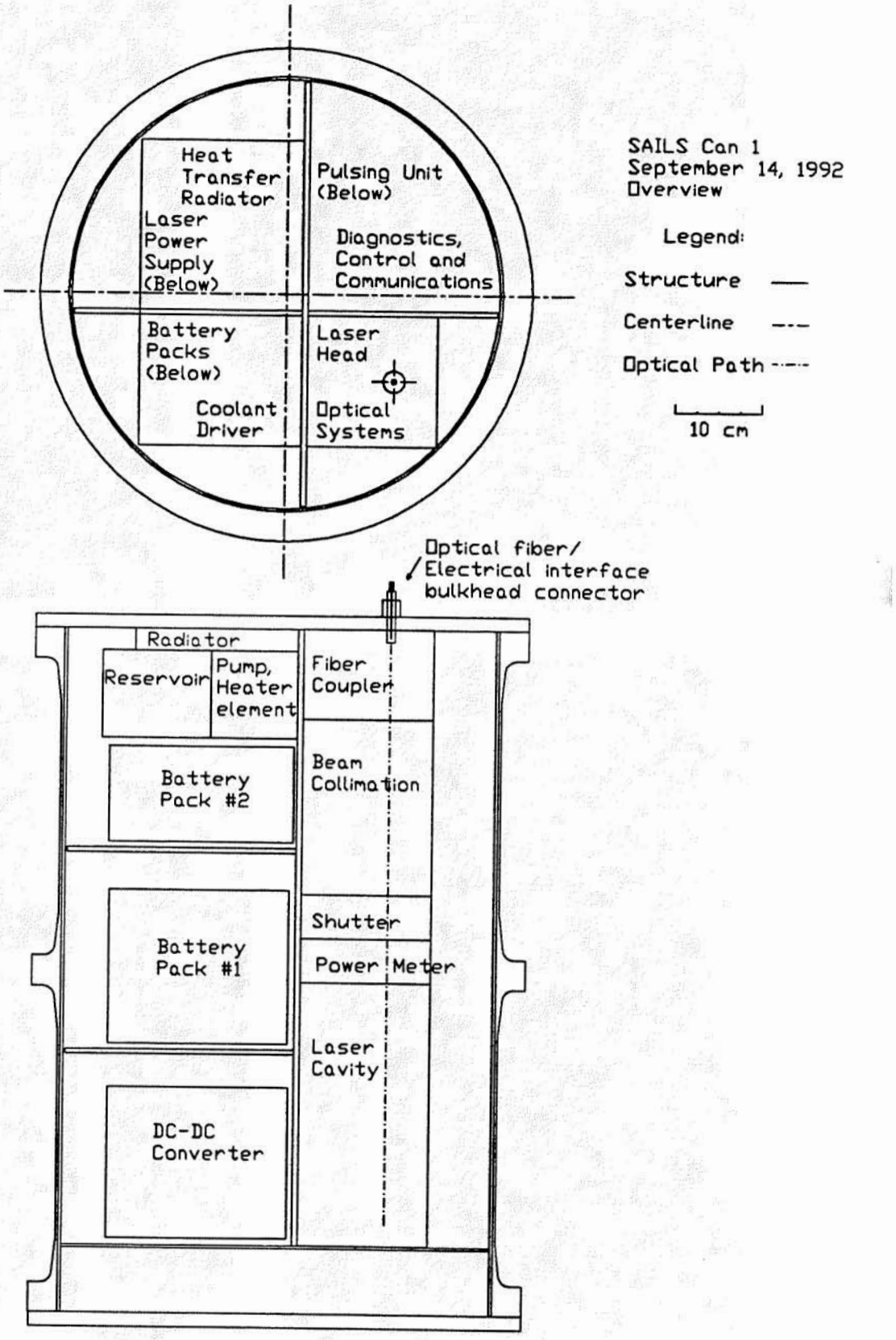

Figure 4 A preliminary design for the SAILS laser GAS can, housing a modified Lumonics LUXSTAR Nd:YAG laser.

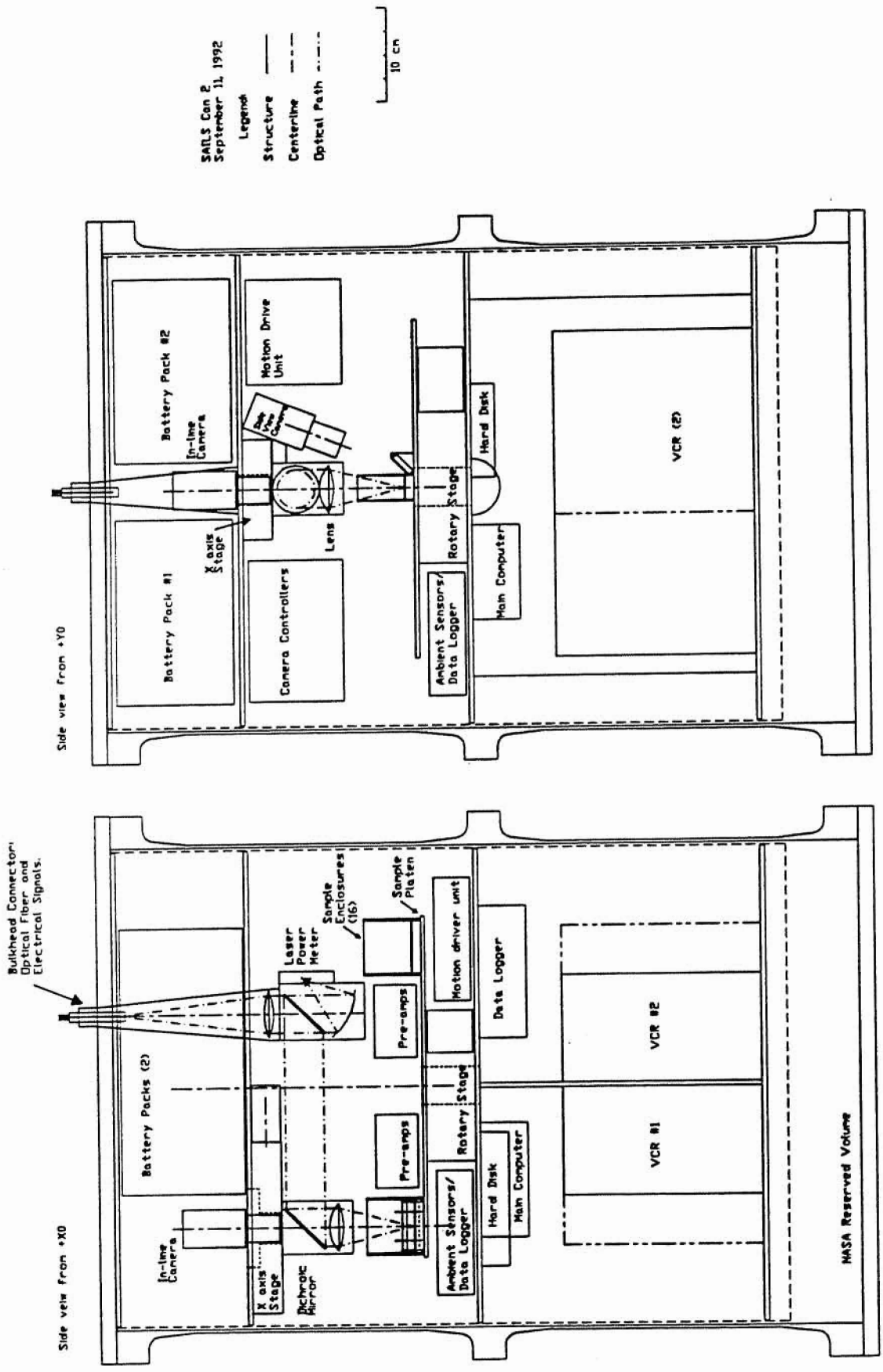

Figure 5 A preliminary design for the SAILS materials processing GAS can. This can will be linked to the laser can by an electrical and fiber-optic cable.

Table 2. A detailed list of the materials and processes to be tested in the SAILS experiment and the purpose of each test.

Material	Thickness	Process	Purpose
316L Stainless Steel: Space Station fluid lines	3.2 mm	Spot/Seam Weld	Non-penetrated bead on plate weld-porosity, root effects, model comparison
		Spot/Seam Braze	Non-penetrated braze-demonstration
	0.73 mm	Spot/Seam Weld	Full penetration bead on plate weld-demonstration, model comparison
		Drill/Cut	Full penetration drill and cut-demonstration, recast layer study
2219 Aluminum: Space Station pressurized modules inner skin	3.2 mm	Spot/Seam Weld	Non-penetrating weld with 4047 filler-porosity, root effects, model comparison
	0.51 mm	Spot/Seam Weld	Full penetration weld with 4047 filler-demonstration, model comparison
		Drill/Cut	Full penetration drill and cut-demonstration, recast layer study
6061 Aluminum: Space Station pressurized modules debris shield	3.2 mm	Spot/Seam Weld	Non-penetrating weld with 4047 filler-porosity, root effects, model comparison
	0.51 mm	Spot/Seam Weld	Full penetration weld with 4047 filler-demonstration, model comparison
		Drill/Cut	Full penetration drill and cut-demonstration, recast layer study
Inconel 718: Space Station cryogenic lines	0.73 mm	Spot/Seam Weld	Full penetration bead on plate weld-demonstration, model comparison
		Drill/Cut	Full penetration drill and cut-demonstration, recast layer study
Copper: Electrical contacts	PC board	Solder	Single or multi-pulse spot solders-demonstration
Kapton: Diagnostic	0.05 mm	Drill/Cut	Laser spot size and energy diagnostic
Lead/Tin: Deep penetration model	3.2 mm	Spot/Seam Weld	Full penetration weld-example of a deep liquid pool, indication of effects of scaling to higher power

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Table 4. SAILS experiment detailed parameter matrix.

Material and Thickness	Process	Defocus (mm)	Power (W)	Energy/ Pulse (J)	Pulse Rate (Hz)	Pulse Length (ms)	Peak Power (W)	Speed (mm/s)
316L Stainless 3.2 mm	Spot/Seam Weld	1.05	50	9	5.5	4.3	2100	2
	Spot/Seam Braze							
316L Stainless 0.73 mm	Spot/Seam Weld	1.05	50	9	5.5	4.3	2100	2
	Drill/Cut	0	50	3.3	15	1.1	3000	1
2219 Aluminum 3.2 mm	Spot/Seam Weld w. filler	0.5	50	5.0	10	1.7	2950	2
2219 Aluminum 0.51 mm	Spot/Seam Weld w. filler	0.5	50	5.0	10	1.7	2950	2
	Drill/Cut	0.2	50	2.4	21	0.8	3000	
6061 Aluminum 3.2 mm	Spot/Seam Weld w. filler							
6061 Aluminum 0.51 mm	Spot/Seam Weld w. filler							
	Drill/Cut	0.2	50	2.4	21	0.8	3000	
Inconel 718 0.73 mm	Spot/Seam Weld							
	Drill/Cut							
Copper PC board	Solder							
Kapton 0.05 mm	Drill							
Lead/Tin 3.2 mm	Spot/Seam Weld	0.9	18	3.5	5.5	5.0	700	2

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